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Anomalous optical properties of fibrous tremolite, actinolite, and ferro-actinolite

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ABSTRACT

The fibrillar growth habit and {100} twinning of fibrous amphiboles tend to produce anomalous optical properties. Commercial amosite and crocidolite always exhibit uniaxial-like optical properties including parallel extinction and two principal indices of refraction. Fibrous members of the actinolite series, however, exhibit a range in optical properties from normal to anomalous. The types of anomalous optical properties that can be displayed by asbestiform members of the actinolite series are described based on a study of twelve samples. One sample displays uniaxial-like properties, nine display partial development of uniaxial-like properties, and two contain fibers with both orthorhombic and monoclinic optical properties. "Byssolitic" samples of the actinolite series, a fibrous non-asbestiform habit, contain fibers that do not go to extinction in sections on or near (010), probably as a result of {100} twinning. Although anomalous optical properties may confound the identification of fibrous amphiboles, in most cases the refractive indices are predictable and can be used for identification. Because of the range in optical properties, especially extinction angle, reliance solely on parallel extinction to distinguish asbestos from non-asbestiform varieties is not recommended. The fibrillar structure, however, remains the hallmark of the asbestiform habit.

INTRODUCTION

Asbestos is a commercial term for exploitable deposits of fibrous minerals that possess desirable physical properties, including long, thin, easily separable fibers with enhanced tensile strength. In the mineralogical sense, the term asbestiform refers to a specific habit and can be used in conjunction with any mineral name. Although many minerals are known to possess an asbestiform habit (Zoltai 1979), the federal regulatory definition of asbestos includes only chrysotile and the asbestiform varieties of cummingtonite-grunerite, riebeckite, tremolite, actinolite, and anthophyllite (Title 40, Code of Federal Regulations, Part 61 and Part 763; Title 29, Code of Federal Regulations, Part 1910 and Part 1926). Since about 1940, asbestiform cummingtonite-grunerite, known by the commercial name amosite, asbestiform riebeckite, known by the varietal name crocidolite, and chrysotile have been commercially important worldwide; anthophyllite asbestos and tremolite asbestos are of less importance, and actinolite asbestos has not been mined on a large scale.

Polarized light microscopy (PLM) is the primary tool for the characterization of asbestos-containing materials because of the potential to identify both the mineral species and the habit. Methods developed for the analysis of asbestos with PLM (e.g., Perkins and Harvey 1993) provide tables of optical properties derived from the literature on non-asbestiform varieties of the minerals, although a distinction may be made in extinction angles between asbestiform and non-asbestiform varieties. It has long been known that minerals normally possessing inclined extinction in PLM may instead display parallel extinction when asbestiform (Sinclair 1959; Deer et al. 1963)—a fact attributed to the fibrillar structure of asbestos (wherein each fiber is a composite of smaller parallel fibrils) and the limited resolving power of the light microscope (Heinrich 1965; Wylie 1979). The fibrillar structure can result in uniaxial-like optical properties when the widths of the individual fibrils are very small, normally less than a few tenths of a micrometer, and the fibrils are tightly packed and randomly oriented around a common fiber axis (Wylie 1979). The uniaxial-like properties include parallel extinction and two principal refractive indices, $n_{\gamma'}$ and $n_{\alpha'}$. If there is partial ordering of fibrils perpendicular to the fiber axis, or simply a small number of fibrils, the optical properties of the bundles may be monoclinic but with modified indices of refraction and extinction angles. An additional factor that may produce parallel extinction in monoclinic amphiboles is {100} twinning. This twinning geometry alters only those refractive indices on (010), leaving the vibration directions on (100) unaffected, producing orthorhombic, biaxial symmetry.

The predominant commercial types of amphibole asbestos, amosite, and crocidolite, are fairly limited in occurrence because they are associated primarily with banded iron formations. Amosite was mined only in the Transvaal Province in South Africa, and crocidolite was mined in four primary localities, specifically the Transvaal and Cape Provinces in South Africa, Wittenoom Gorge in western Australia, and Cochabamba, Bolivia (Deer et al. 1997; Ross and Virta 2001; Ross 1981). Fibers of amosite and crocidolite from commercially exploited deposits show a high degree of development of the asbestiform habit; more than 90% of the fibers in these samples have widths less than 1.0 μm, and most are less than 0.5 μm (Veblen and Wylie 1993). The smallest fibrils of amosite and crocidolite have widths on the order of 0.1 μm. Amosite and crocidolite have only two indices of refraction, $n_{\gamma'}$ and $n_{\alpha'}$, as demonstrated in the National Institute of Standards and

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Technology (NIST) Standard Reference Material (SRM) 1866a[1], and parallel extinction, and therefore display the uniaxial-like properties expected from a fibrillar structure. Interference figures observed on sections parallel to the fiber axis are typical of those normal to an optic axis, i.e., flash figures. Because of the limited occurrences of amosite and crocidolite and the general uniformity of their optical properties, these types of asbestos can be identified routinely in PLM analyses, notwithstanding their anomalous optical properties.

Asbestiform members of the tremolite–actinolite–ferro-actinolite series, hereafter referred to as actinolite-series asbestos, are more widely distributed as minor constituents of metamorphosed mafic, ultramafic, and carbonate rocks, although they are extremely rare in commercial products. Because of its wider distribution, actinolite-series asbestos commonly can be found in rocks exposed at the surface, either naturally or by mining or excavation, causing a potential environmental (i.e., non-occupational) hazard. Actinolite-series asbestos also can be found as a contaminant of other industrial mineral products. The recognition of environmental hazards has increased recently, in part due to documented asbestos disease in local populations exposed to naturally occurring asbestos in Europe and Asia (Hillerdal 1999; Paoletti et al. 2000) and New Caledonia (Luce et al. 2000). The Environmental Protection Agency (EPA) is currently reviewing the asbestos risk assessments, particularly with respect to environmental exposures (EPA 2001 Asbestos Health Effects Conference, Oakland, California, May 24–25, 2001). The recognition of possible environmental hazards has prompted the State of California to map the location of all ultramafic rocks in the state for their potential to contain actinolite-series asbestos and chrysotile asbestos (Churchill and Hill 2000).

Although all asbestos, by definition, contains fibrils of very fine width that occur in bundles[2], samples of actinolite-series asbestos may also contain fibers several micrometers in width that exhibit normal, monoclinic biaxial optics with extinction angles and refractive indices typical of non-asbestiform specimens. Such large fibers were found in approximately half of the actinolite-series asbestos samples reported by Verkouteren and Wylie (2000); they are compositionally the same as the finer fibers, and their optical properties, as reported in that paper, were taken to represent the whole. The fibers in the remaining actinolite-series asbestos samples exhibit only anomalous optical properties, and those properties are described in this paper. Anomalous optical properties are characteristic of these samples but also occur in one form or another in the finer portion of all samples of actinolite-series asbestos. The samples used in this study come primarily from non-commercial deposits that are located throughout the world; descriptive information, including locality, is given in Verkouteren and Wylie (2000). Although the properties determined here are for the actinolite series, the models for the development of anomalous optical properties can be applied generally to monoclinic amphibole asbestos.

EXPERIMENTAL METHODS

All samples were analyzed for chemical composition and unit-cell parameters by electron microprobe (EMP) and powder X-ray diffraction (XRD methods), respectively, with the procedures described by Verkouteren and Wylie (2000). All samples are fibrous: the majority are asbestiform and the remainder are "byssolitic."[3] Optical properties were measured by mounting individual fibers (normally at least 2 μm in width) on the ends of glass spindles for orientation with a goniometer on the light microscope. Fibers were rotated about the fiber axis (parallel to *c*) to observe extinction. Principal vibration directions in fibers with inclined extinction were located by rotation about *c* to find the unique position of parallel extinction on (100) where $Y = b$. The (010) plane containing Z and X was found by a 90° rotation about the fiber axis from (100). For those fibers displaying parallel extinction throughout rotation about the fiber axis, the principal vibration directions perpendicular to elongation were located empirically by measurement of refractive indices at 10° intervals throughout rotation. Refractive index measurements were made by determining the wavelength at which a calibrated immersion liquid of known refractive index and the solid match (Bloss 1981; Verkouteren et al. 1992). For those samples displaying uniaxial-like optical properties, or for samples with fibers that were too small for mounting, measurements were made from oil immersion slide mounts on a large number of fibers.

RESULTS

Optical properties and the fibrillar structure

Fibers in immersion slide mounts lie preferentially on surfaces parallel to *c* and display extinction angles ranging from 0° on (100) to the true extinction angle on (010) (Fig. 1). [The maximum extinction angle observed on {*hk*0} sections for monoclinic crystals with $Y = b$ is not necessarily equivalent to $c \wedge Z$. Angles exceeding the true extinction angle can be found on sections between (100) and (010) if the obtuse bisectrix lies within 45° of *c* (Su and Bloss 1984). For the actinolite series, the maximum extinction angle exceeds $c \wedge Z$ by less than 1°]. Extinction angles on (010) for the actinolite series are typically between 13 and 18°, although values as high as 24° at a ferro-actinolite content of approximately 28% have been reported (Deer et al. 1997). Extinction angles larger than 10° were not found in the ten samples studied (Table 1), despite observation of a large number of fibers in slide mounts. For the few samples for which

[1] NIST SRMs for optical properties of asbestos include SRM 1866a, Common Commercial Asbestos, and SRM 1867, Uncommon Commercial Asbestos. Information available at http://srmcatalog.nist.gov.

[2] Asbestos is recognized under the light microscope by the following characteristics for the population of fibers: (1) mean aspect ratios ranging from 20:1 to 100:1 or higher for fibers longer than 5 μm; (2) very thin fibrils, generally less than 0.5 μm in width; (3) parallel fibers occurring in bundles; and (4) one or more of the following: fiber bundles displaying splayed ends, matted masses of individual fibers, and fibers showing curvature.

[3] A term adopted by the asbestos community to describe a stiff (brittle), fibrous variety of amphibole that is not asbestiform, following Dana (1932). Recommended by the IMA (Leake 1978) for removal from the nomenclature, but retained in this paper because of the significance to regulatory terminology.

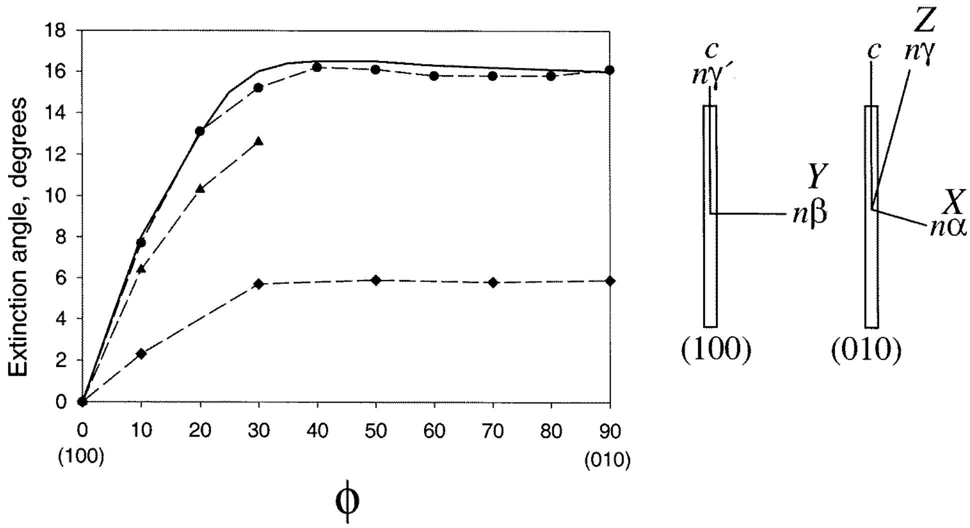


FIGURE 1. Extinction characteristics of asbestos and "byssolitic" fibers. Model (solid line) of extinction behavior between (100) and (010) given $c \wedge Z$ of 16° and 2V_Z = 105° determined graphically according to guidelines in Bloss (1981). Rotation axis ϕ is parallel to c. Fibers of actinolite-series asbestos with normal optical properties (sample 253, circle) and with anomalous optical properties (sample 38, diamond) and a "byssolitic" fiber showing incomplete extinction (triangle). Schematic drawings show orientation of refractive indices with fiber morphology for (100) and (010).

some of the fibers could be mounted on the spindle stage, the extinction angles observed during rotation about the fiber axis were anomalously low, as shown in Figure 1.

The refractive indices of the samples in Table 1 were determined by measuring the maximum value at the extinction position closest to the fiber axis ($n_{\gamma'}$) and the minimum value perpendicular to this position ($n_{\alpha'}$) in a large number of fibers in slide mounts. The variability in each index was determined as the range in measured values, even though a relatively small number of fibers may define the ends of the ranges. (Measurements from oriented fibers would allow for the calculation of the population averages for the refractive indices, but this was not possible due to the extremely small size of the fibers.) For most of the samples, $n_{\gamma'}$ is equal to or smaller than the model value of n_γ predicted for that composition in the actinolite series (Verkouteren and Wylie 2000), and $n_{\alpha'}$ is equal to or larger than the model value of n_α (Fig. 2). This result is generally consistent with that expected from a fibrillar structure. The two samples that do not follow this general result, samples 38 and 132, are discussed later.

Only one of the samples, sample 255, displays the uniaxial-like optical properties typical of amosite and crocidolite, with parallel extinction for all fibers in grain mount, and two refractive indices. The ranges in $n_{\gamma'}$ and $n_{\alpha'}$ are not significantly larger than measurement error (see Table 1), and the value of $n_{\alpha'}$ is close to the arithmetic average of the model values of n_α (1.619) and n_β (1.633). The other samples in Table 1 are not strictly uniaxial-like, as fibers with inclined extinction are observed (although always with extinction angles <10°), and the variability in $n_{\alpha'}$ is larger than expected from measurement error. In these samples, the range in $n_{\alpha'}$ is equal to or greater than 0.004, whereas, in general, the range in $n_{\gamma'}$ is less than 0.004. Because the fibrils have a common axis c in the fiber bundle, but have any orientation perpendicular to c, they can express any refractive index perpendicular to elongation from n_α on (010) to n_β on (100). The refractive indices parallel (or near parallel) to elongation are restricted to values between n_γ on (010) and $n_{\gamma'}$ on (100), which is a much smaller range. Therefore, in fiber bundles with partial ordering of fibrils, or in fiber bundles that contain only a few fibrils, it would be expected that there would be

TABLE 1. Asbestiform tremolite, actinolite, and ferro-actinolite with partial to complete development of uniaxial-like optical properties, sorted by ferro-actinolite content [(Fe + Mn)/(Fe + Mn + Mg)] × 100 = X_{Fe}.

Sample*	X_{Fe}	$n\gamma'$		$n\alpha'$		$c \wedge Z$°	δ	Model values		
		max	range	min	range			n_γ	n_α	δ
37	3.5	1.633(1)	0.001	1.606(1)	0.012	<10	0.027	1.633(1)	1.606(1)	0.027
238	5.4	1.632(1)	0.002	1.611(1)	0.004	<10	0.021	1.635(1)	1.607(1)	0.028
242	5.5	1.634(1)	0.004	1.606(1)	0.008	<10	0.028	1.635(1)	1.608(1)	0.027
140	6.6	1.636(1)	0.001	1.612(1)	0.008	<10	0.024	1.636(1)	1.609(1)	0.027
255	17.4	1.640(1)	0.001	1.624(1)	0.002	0	0.016	1.643(2)	1.619(2)	0.024
137	17.6	1.642(1)	0.002	1.618(1)	0.008	<10	0.024	1.643(2)	1.620(2)	0.023
38	38.5	1.640(1)	0.003	1.612(1)	0.022	<10	0.028	1.658(2)	1.635(3)	0.023
132	51.8	1.656(1)	0.002	1.630(1)	0.006	<10	0.026	1.667(2)	1.641(4)	0.026
66	70.2	1.679(1)	0.002	1.662(1)	0.004	<10	0.017	1.680(3)	1.651(5)	0.029
115	71.8	1.685(1)	0.010	1.658(1)	0.006	<10	0.027	1.681(3)	1.651(5)	0.030

Note: Uncertainties in the least significant digit given in parentheses.
* See Verkouteren and Wylie (2000) for compositions, cell parameters, sample localities, etc.
† Calculated for measured X_{Fe} from Verkouteren and Wylie (2000).

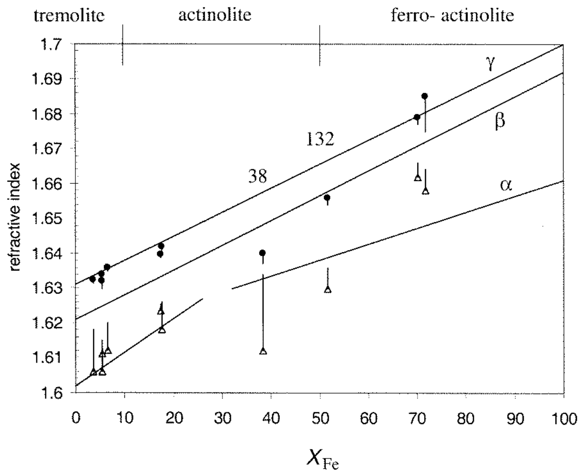


FIGURE 2. Refractive indices of optically anomalous tremolite, actinolite, and ferro-actinolite asbestos. Model (solid lines) n_α, n_β, and n_γ for the actinolite series from Verkouteren and Wylie (2000). Maximum values of $n_{\gamma'}$ (circles) and minimum values of $n_{\alpha'}$ (triangles) with vertical lines indicating ranges. Samples identified in Table 1. [(Fe + Mn)/(Fe + Mn + Mg)] × 100 = X_{Fe}

a higher variance in index of refraction perpendicular to the fiber axis than along the fiber axis.

Sample 115 is unique in having a very large range in $n_{\gamma'}$ of 0.010. Large variations in $n_{\gamma'}$ can be produced by non-parallel fibrils within a bundle, which was thought to be the source of the variation observed in $n_{\gamma'}$ for amosite in SRM 1866a (NIST 1991). Samples 132, 66, and 115 are all from South Africa; sample 132 is also an outlier in having $n_{\alpha'}$ lower than the model value of n_α and $n_{\gamma'}$ lower than model value of n_β. Based on the differences among these three samples, there is a large compositional range in the asbestiform ferro-actinolite from South Africa, and it is possible that some of the irregularities observed in samples 115 and 132 can be explained by compositional variability within each sample. Although the unit-cell dimensions of both samples are consistent with the model values for their compositions, XRD data would not be sensitive to a minor amount of a compositionally different actinolite that could be intergrown in the fiber bundles. The EMP are restricted to polished areas greater than a few micrometers in diameter, which are usually those areas where the fibrils are wider. This restriction can result in a sampling bias such that the true chemical variability cannot be determined.

Sample 38 has $n_{\alpha'}$ lower than model n_α, $n_{\gamma'}$ lower than model n_β, and a birefringence ($n_{\gamma'}$–$n_{\alpha'}$) larger than the model value. In addition, the range in $n_{\alpha'}$ is noteworthy in that its magnitude is greater than the model value of n_β–n_α. These features cannot readily be explained by either compositional variation in the amphibole or growth habit. Most amphibole asbestos is known to be intergrown with sheet silicates (Veblen and Wylie 1993), which normally have lower indices of refraction; however, there is no evidence of another phase from the XRD pattern of this sample. Fluorine may also lower indices of refraction, but we have examined this sample by wavelength dispersive spectrometry on the EMP and there is no F present above the detection limit of 0.2 wt%. This sample has physical characteristics that indicate extensive weathering has occurred: the fibers have low tensile strength (atypical for asbestos) and crush to a powder readily. The few regions of the sample that can be polished smooth appear to be relic areas within an otherwise altered material. The fibrillar structure of asbestos provides extensive surface area for leaching by weathering, and Mg and/or Ca loss on the surface could affect the indices of refraction. If weathering were involved in lowering the indices of refraction, uneven weathering might also explain the variability.

Pseudo-orthorhombic fibers

Fibers exhibiting orthorhombic optical properties (parallel extinction, three principal indices of refraction) were found in several actinolite-series asbestos samples that also contain the larger fibers with normal, biaxial optical properties, as described in the introduction. The fibers exhibiting orthorhombic optical properties were identified during the course of mounting fibers for the spindle stage and were found in sufficient abundance in two samples. The values in Table 2 are based on measurements of two or three optically orthorhombic fibers from each sample compared with more than six fibers each of the optically monoclinic fibers.

There is no evidence from XRD analysis for the presence of orthorhombic amphiboles in the two samples. The fibers that are optically orthorhombic are, in physical appearance, identical to the fibers that are optically monoclinic, and are generally of the same dimensions. Fibers of both types (orthorhombic and monoclinic) from each sample were analyzed in the SEM to compare compositions; all fibers contained Ca and produced energy dispersive spectra consistent with the bulk compositions.

The refractive indices of both types of fibers from each sample are very similar. There is a slight decrease of 0.002 to 0.004 in n_γ for the optically orthorhombic fibers; n_α and n_β are the same for the two fiber types within the uncertainty of the measurements. The orthorhombic optical properties are probably a product of twinning on {100}, although the simple model would also predict an increase in n_α, which we do not see in our data. However, the consistency in refractive indices within the population of the optically orthorhombic fibers and the parallel extinction points to a mechanism such as twinning, rather than to partial ordering of fibrils or fiber bundles containing only a few fibrils.

TABLE 2. Asbestiform samples containing fibers with normal monoclinic optical properties and fibers with orthorhombic optical properties

		Orthorhombic				Monoclinic			
Sample	X_{Fe}	n_γ	n_β	n_α	c∧Z°	n_γ	n_β	n_α	c∧Z°
29	0.7	1.626(1)	1.617(1)	1.601(1)	0	1.6284(5)	1.6173(5)	1.6003(5)	15.8(5)
253*	15.7	1.635(1)	1.628(1)	1.613(1)	0	1.6393(5)	1.6288(5)	1.6126(5)	15.9(5)

Note: Uncertainties in the least significant digit given in parentheses.
* SRM 1867 actinolite asbestos.

Fibers showing incomplete extinction on (010)

Four samples of "byssolitic" tremolite and actinolite [samples 12, 30, 61, and 201 from Verkouteren and Wylie (2000)] are dominated by fibers that do not go to extinction on or near (010) (Fig. 1). The fibers show the expected parallel extinction every 180∞ during rotation about the fiber axis, indicating that extinction on (100) is normal, and the values of n_β measured for the 4 samples agree with model values for the actinolite series. The fibers are typically flattened and broadly curved on (100) resulting in a strong preferred orientation for fibers in slide preparation; most of the fibers either show parallel extinction or no extinction (Fig. 3a). The extinction characteristics can be explained by {100} twinning, with twin lamellae of a size too small to be observed by light microscopy, but large enough to produce multiple indicatrices. It is possible that the anomalous extinction observed in some samples of arfvedsonite, in which there is no extinction on (010), can also be explained by {100} twinning, although the explanations previously offered for the behavior have generally focused on strong absorption (Deer et al. 1997).

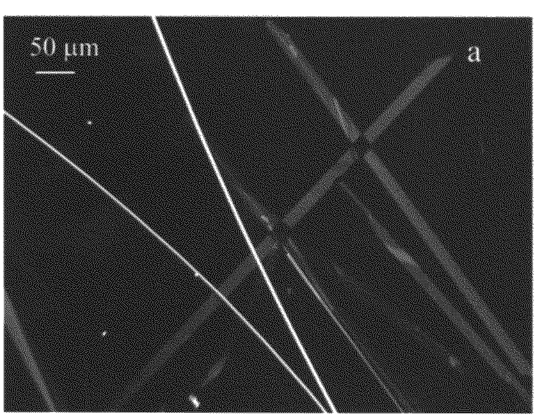
Application to unknowns

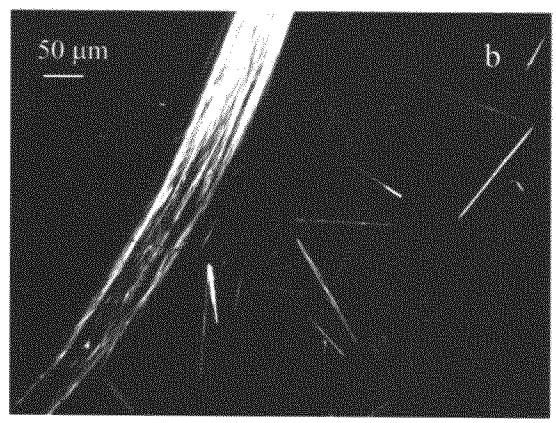
The amphibole most likely to be confused with optically anomalous tremolite and actinolite is anthophyllite. Both crocidolite and amosite were once thought to be orthorhombic based on their optical properties. The optically orthorhombic fibers reported in Table 2 would be virtually impossible to distinguish from anthophyllite with PLM, but we have not found these to be the primary component of any sample. The fibers reported in Table 1 should not be confused with anthophyllite, as most display inclined extinction. The one sample with parallel extinction, sample 255, has only two refractive indices, and would not be confused with optically normal anthophyllite, which is biaxial. If the optical properties of anthophyllite asbestos were altered by the fibrillar structure, it is likely that the birefringence would be even smaller than that observed for sample 255 because the birefringence of anthophyllite (0.016–0.028) (Deer et al. 1997) is generally lower than the birefringence of the actinolite series (0.023–0.035).

The sample whose identity would remain ambiguous based solely on optical properties is sample 38. The birefringence of the sample is a little high for actinolite given n_γ = 1.640 (model δ = 0.025), and the range in $n_{\alpha'}$ is not consistent with actinolite. The optical data do not support the identification of any other amphibole, however, as most have higher refractive indices or lower birefringences. In general, optical properties are not used as the sole basis for the identification of an amphibole (Leake et al. 1997). It is because of the comprehensive data reported by Verkouteren and Wylie (2000) that optical properties can be used, when they are consistent with the series, as a basis for identification of actinolite-series amphiboles.

Discussion

The proper identification of the mineral in an asbestos sample is not an esoteric or academic exercise, but an important component in the current and future understanding of asbestos disease. Differences in disease potential with respect to miner-





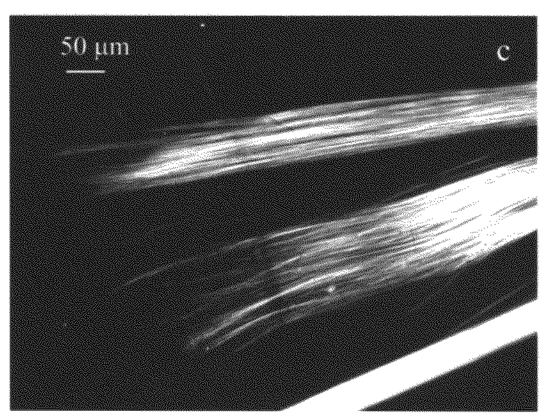


Figure 3. Photomicrographs using cross-polarized light with analyzer vibration direction oriented E-W. (A) Sample 12 "byssolitic" actinolite. Low-birefringence fibers lie on (100) and exhibit parallel extinction; high-birefringence fibers do not go to extinction during rotation of the stage. (B) Sample 253 actinolite asbestos. Individual fibers and fibers in bundles show extinction angles ranging from 0 to 16°. Fibers with inclined extinction range in width to approximately 3 µm. (C) Sample 255 actinolite asbestos. All fibers and fiber bundles exhibit parallel extinction.

alogy have been identified, even within the amphiboles, with anthophyllite thought to be much less capable of producing mesothelioma than crocidolite (Hillerdal 1999). The extension of asbestos analysis from the typical, commercial asbestos products to environmental sources of asbestos will require more analytical rigor than previously necessary, simply because of the wider range of possible amphiboles. For example, the asbestos found as a contaminant of vermiculite in Libby, Montana is winchite (Wylie and Verkouteren 2000), and the asbestos found in Biancavilla, Sicily, is fluoro-edenite (Gianfagna and Oberti 2001); both are sources of environmental exposure. Proper mineralogical characterization is needed to trace any contamination found in soils, mineral products, dusts, lung tissue, etc., to the source of asbestos in the environment.

The range in fibril size for actinolite-series asbestos, as indicated by extinction characteristics, has implications for the quantitative analysis of asbestos in bulk materials. All methods for quantitative analysis of amphibole asbestos must take into account the shapes of the particles to distinguish cleavage fragments from asbestos. Ageneral assumption, based on the models of amosite and crocidolite, is that any optically visible asbestos fiber is actually a bundle of fibrils, and will therefore display parallel, or close to parallel, extinction. Inclined extinction (>5°) for fibers wider than 1 μm was used by Schneider et al. (1998) to distinguish asbestos from non-asbestos particles.

Fibers of amosite and crocidolite that are 1 μm wide uniformly display uniaxial-like optical properties because they contain a large number of fibrils. Fibers of actinolite-series asbestos that are 1 μm wide do not uniformly exhibit uniaxial-like optical properties, either because of a small number of fibrils or partial ordering of fibrils. Therefore, the requirement in Schneider et al. (1998) for all asbestos fibers wider than 1 μm to exhibit extinction within ±5° of the vibration direction of the polarizer is not appropriate for many samples of actinolite-series asbestos. Furthermore, parallel extinction is not an exclusive indicator of fibrillar growth habit in monoclinic amphiboles, as it is always observed on (100) and can be produced by {100} twinning. The "byssolitic" fibers described in this paper and in Dorling and Zussman (1987) show a high degree of (100) preferred orientation in grain mount and a large percentage of the fibers will show parallel extinction.

A general rule that allows discrimination of the hazardous material in an asbestos sample is clearly a difficult matter. Although it was given very careful consideration by Schneider et al. (1998), it remains an area of concern for quantitative analysis of asbestos in environmental samples and industrial minerals. However, the fibrillar structure of asbestos remains the most reliable discriminator for populations of asbestos.

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